

GAS-COUPLED, PULSE-ECHO ULTRASONIC CRACK DETECTION AND THICKNESS GAGING*

C. M. Fortunko,[†] R. E. Schramm,[†] C. M. Teller,[‡] G. M. Light,[‡]
J. D. McColskey,[†] W. P. Dubé,[†] and M. C. Renken[†]

[†] National Institute of Standards and Technology
325 Broadway
Boulder, Colorado 80303

[‡] Southwest Research Institute
6220 Culebra Road
San Antonio, Texas 78228

INTRODUCTION

Ultrasonic inspection is a standard method to assess the integrity of large-diameter oil pipelines. However, similar methods applied to natural-gas pipelines present a considerably greater challenge; gas is a poor coupling agent for the probing ultrasonic signals between the transducer and the pipe wall. Natural gas exhibits a very low specific acoustic impedance (300 Rayls for methane at atmospheric pressure) compared to oil (1.5 MRayls and higher). Consequently, large ultrasonic-signal transmission losses occur at the transducer/gas and pipe-wall/gas interfaces. To circumvent this obstacle, past exploratory developments included the use of a liquid-filled wheel [1], electromagnetic-acoustic-transducer (EMAT) [2], and liquid-slug technologies [3]. While prototypes of high-speed, in-line inspection systems employing such principles do exist, all exhibit serious operational shortcomings that prevent widespread commercial exploitation.

Our measurements in high-pressure gas demonstrate an ability to see back-wall as well as front-wall signals. This points to the technical feasibility of an alternative approach to the important problem of high-speed, in-line ultrasonic inspection of natural-gas pipelines. Specifically, we show that it is possible to operate a gas-coupled

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ultrasonic inspection system in the classic pulse-echo configuration to detect simulated flaws and observe wall-thickness variations. Furthermore, since our experimental results demonstrate good signal-to-noise (S/N) characteristics, we hope that our approach may provide the enabling technology for future high-speed, in-line ultrasonic inspection systems for natural-gas pipelines, risers, and similar structures.

OBSTACLES TO PULSE-ECHO OPERATION

Until recently, the general belief was that the gas-coupled, pulse-echo ultrasonic inspection concept would not be feasible. This was due to unacceptably large signal losses from (1) high absorption in the gas at megahertz frequencies, and (2) very high signal-reflection losses at the gas-solid interfaces because of the specific impedance mismatch. However, we showed [4] that wide-band, well-damped ceramic transducers, and high-dynamic-range receiver amplifiers can overcome such effects.

That work [4] also showed that high ultrasonic absorption is not among the major obstacles to overcome when designing gas-coupled, pulse-echo ultrasonic systems at megahertz frequencies. In fact, the ultrasonic absorption coefficient in nitrogen is only 0.72 dB/mm at 2.25 MHz at 0.1 MPa (15 psi) and decreases inversely with pressure [5]. The amount of ultrasonic absorption in natural gas is unknown because of its variable composition. However, methane is the major component of all natural gases, ranging from 79 to 97 mole % [6]. Absorption constants of pure methane are well known, both experimentally and theoretically [7]. At 2.25 MHz and 0.1 MPa, the absorption coefficient in pure methane is approximately 0.62 dB/mm. However, actual losses may be significantly greater because of excess absorption caused by molecular relaxation effects in other constituents.

In this work, we have not considered the effects of finite-amplitude saturation caused by the nonlinear behavior of natural gas. Future investigation of such effects will be necessary, since they may limit the S/N performance characteristics of practical inspection systems. Mechanical and electrical impedance-matching techniques result in increased interference between the probing and reflected signals, so we do not use such techniques. Other effects also can be important, such as (1) electrical-breakdown, mechanical, and thermal limits of piezoelectric transducers limiting power generation, and (2) impact of gas motion on the signal characteristics.

EXPERIMENTAL CONFIGURATION

Figure 1 shows the block diagram of the experimental setup developed at NIST to study ultrasonic-wave propagation in high-pressure gases and evaluate various ultrasonic inspection concepts. The setup uses a cylindrical pressure vessel, 305 mm (12 in) in diameter and 610 mm (24 in) in length. The pressure vessel can accommodate a variety of gases at pressures up to 10 MPa (1500 psi) and has appropriate feed-throughs for sample and transducer-motion control, signal handling, and pressure and temperature monitoring. Inside the vessel, a flexible stage with multiple degrees of freedom manipulates both the transducer and samples. In our experimental work, we remotely commanded four position-adjustment motors to

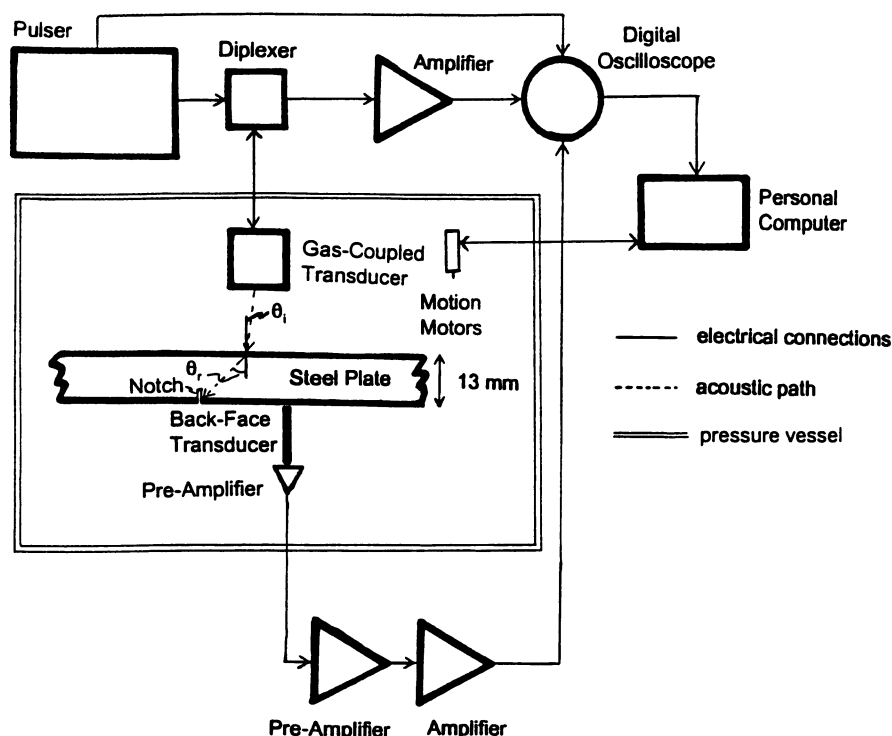


Fig. 1 Outline of feasibility demonstration. The specimens and transducers are inside a pressure vessel rated to 10 MPa (1500 psi).

manipulate the Z coordinate of the sample and the X, Y, and θ coordinates of the pulse-echo transducer. The coordinate θ is the angle in the sagittal plane between the transducer symmetry axis and plate-surface normal.

A piezoelectric-ceramic transducer, 13 mm (0.5 in) in diameter, generates and receives the probing ultrasonic signals. The transducer exhibits a center frequency of 2.25 MHz when operated in water. However, in gas it is somewhat lower. This may be caused by the frequency-dependent attenuation of sound in the gas. To generate, detect, and condition the ultrasonic signals, we use a square-wave pulser with 8 kW available peak power at 400 V, a special diplexer circuit, and a high-input-impedance receiver amplifier with 64 dB dynamic range and 60 MHz bandwidth. Manual, stepped attenuators control the output pulse, available power levels, and receiver-amplifier gains. We also use a 400-Msamples/s, 8-bit digital storage oscilloscope (DSO) to record the signal waveforms. A dedicated computer controls the setup.

As shown in Fig. 1, there is another transducer, coupled directly to the back surface of the flat-plate specimen. This is a pin transducer, 1.4 mm (0.06 in) in diameter, to provide ultrasonic-beam diagnostics and aid in alignment. Because transducers of this type inherently exhibit very small capacitances (typically 20 pF) compared to the total capacitance of the coaxial cable (nearly 300 pF here), it has a special very-low-noise, voltage-mode preamplifier attached.

The specimens were two surface-ground flat steel plates. Each is 114 mm (4.5 in) long, 44 mm (1.75 in) wide, and 13 mm (0.5 in) thick. In our experiments, we arranged the two specimens side by side. The two plates are identical except that they contain thin, surface-breaking notches made by standard electro-discharge machining (EDM) procedures. The notch depths are 20% and 40% of the nominal plate thickness, *i.e.*, 2.5 mm (0.1 in) and 5.1 mm (0.2 in). The notches have 0.3-mm (0.01-in) mouth widths and are 44 mm (1.75 in) long.

In principle, the experimental arrangement shown in Fig. 1 is useful for measuring the thickness of the plate, finding delaminations in the plane of the plate, and detecting vertical cracks. Plate-thickness measurements and delamination detection are best made using longitudinal-wave signals that propagate along the plate-surface normal. Such signals result from compressional-wave signals in the gas that propagate along the plate-surface normal direction ($\theta_i = 0^\circ$). On the other hand, vertical-crack detection is best accomplished with longitudinal- or shear-wave signals that propagate at an angle (θ_r) with respect to the plate-surface normal. To generate such signals, the symmetry axis of the pulse-echo transducer must rotate in the sagittal plane to satisfy Snell's law for either longitudinal- or shear-wave signals. Because sound propagates much more slowly in a gas than in water, 300-500 m/s vs. 1500 m/s, the incidence angles of the ultrasonic probes are correspondingly smaller. Furthermore, sensitivity to misalignment is greater for gas-coupled systems. Therefore, achieving proper initial transducer alignment with respect to the plate-surface normal becomes very important.

To prepare the system for experimental work, we first align the transducer symmetry axis along the plate-surface normal at atmospheric pressure. The gas pressure is then brought to the desired pressure, typically 6.9 MPa (1000 psi). Increasing the gas pressure greatly improves the S/N performance of the experimental system, and makes the final alignment of the transducer symmetry axis to maximize the level of the front-surface reflection signal relatively easy. Next, we probe the spatial characteristics of the ultrasonic signals in the plate using the small pin transducer, as shown in Fig. 1.

Figure 2a shows the time-domain appearance of an ultrasonic signal train observed using atmospheric air (1600 m above sea level) when the transducer symmetry axis is along the plate-surface normal. Here, the front surfaces of the transducer and the plate are approximately 34 mm (1.3 in) apart. In Fig. 2a, a triangular marker points to the front-surface reflection signal, at 185 μ s. Figure 2b shows the appearance of the same ultrasonic signal train after increasing the pressure of the coupling gas (nitrogen) to approximately 6.9 MPa (1000 psi) and decreasing the gain of the receiver amplifier by 52 dB. The first signal, corresponding to the direct front-surface reflection, now emerges clearly from the noise, and a second signal, corresponding to the second reverberation between the transducer and plate, is apparent at 370 μ s. The S/N performance of the experimental system improves very rapidly with increased gas pressure and the second reverberation becomes clearly observable even at 0.3 MPa (40 psi). At this point, the final alignment of the transducer symmetry axis with the plate-surface normal is possible.

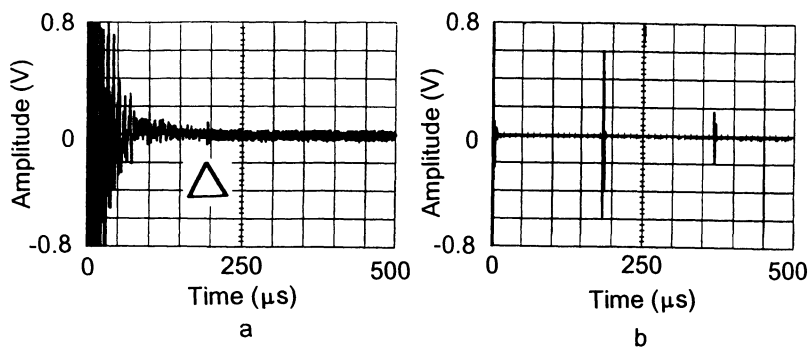


Fig. 2 Effect of pressure on the signal-to-noise performance of the gas-coupled experimental system. The transducer face was 34 mm (1.3 in) from the front face of a steel plate. The incident beam was normal ($\theta_i = 0$) and generated the multiple reflections seen at 185 and 370 μ s.

- a. Atmospheric air, receiver-amplifier gain = 64 dB.
- b. 6.9-MPa (1000-psi) nitrogen, receiver-amplifier gain = 12 dB

To generate longitudinal- and shear-wave signals at an angle with respect to the plate-surface normal, we rotate the symmetry axis of the pulse-echo transducer in the sagittal plane. We then use the pin transducer to learn the spatial and S/N characteristics of the resultant ultrasonic beams. Figure 3 shows the amplitude C-scans found by probing the ultrasonic signals from the back side of the steel plate.

EXPERIMENTAL RESULTS

Figure 4 shows the time-domain signals resulting from the direct reflection off the front surface of the plate (a). The following signals are multiple reverberations within the plate (b and c). Here, the transducer-plate separation distance was 38 mm (1.5 in) and the pressure (nitrogen) was 6.9 MPa (1000 psi). The time-domain separation between the ultrasonic reverberations in the flat plate (b and c) is approximately 4 μ s, consistent with the nominal plate thickness of 12.7 mm (0.5 in). Measurement of the time interval between successive reverberations indicates the thickness of the plate and the presence of delaminations.

In principle, both longitudinal- and shear-wave signals are useful in a pulse-echo configuration for flaw detection. In water-coupled systems, longitudinal-wave signals are preferable. Although in our experiments we observed both longitudinal- and shear-wave flaw signals, the latter clearly separate from the front-surface reflection signals. The A-scan in Fig. 5 illustrates this effect. The longitudinal-wave flaw signal occurs at only 6 μ s after the first observable front-surface reflection. Although we can

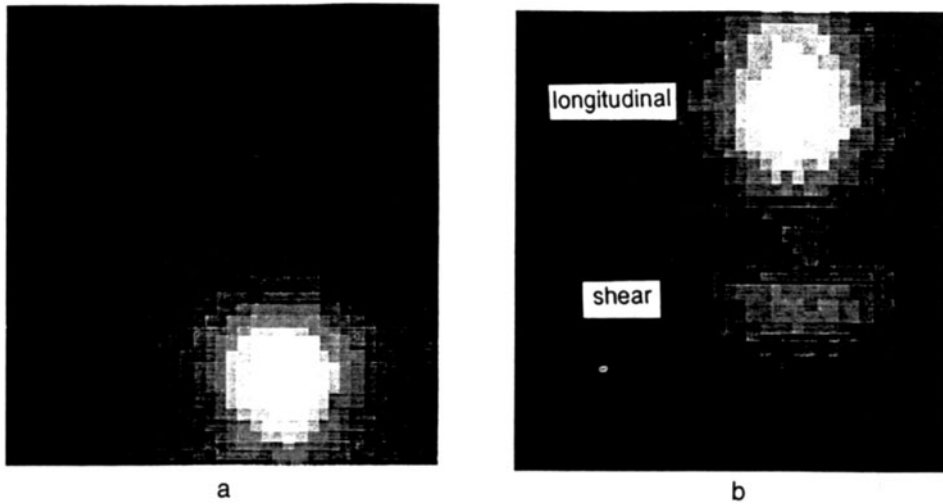


Fig. 3 Amplitude C-scans of signals transmitted through 8 mm of atmospheric air and 13 mm of steel. Each pixel is 0.5 mm square. The scan region is 20 mm square. The 6-dB-down points are about 5 mm from the beam center.

- a. Normal incidence, $\theta_i = 0^\circ$.
- b. $\theta_i = 2.5^\circ$ to produce longitudinal ($\theta_r = 45^\circ$) and shear ($\theta_r = 23^\circ$) signals inside the plate.

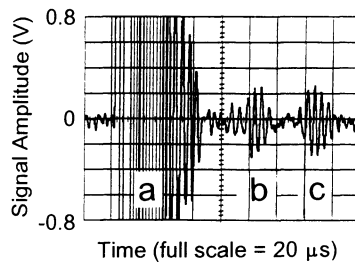


Fig. 4 Typical A-scan: gage pressure = 6.9 MPa (1000 psi), gas path = 38 mm (1.5 in), plate thickness = 12.7 mm (0.5 in), amplifier gain = 64 dB, $\theta_i = 0^\circ$.

- a. Direct compressional-wave reflection from front face of plate.
- b. Second longitudinal-wave reverberation in the plate.
- c. Third longitudinal-wave reverberation in the plate.

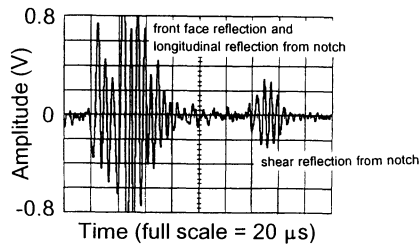


Fig. 5 Expanded A-scan showing a direct reflection from the front surface of the plate and a shear-wave reflection from an EDM notch, 40% in depth. $\theta_i = 4.5^\circ$, $\theta_r = 45^\circ$.

detect the presence of the vertical notch (40% of wall thickness) by monitoring the behavior of the interferences between the two signals, the process is not reliable. On the other hand, the shear-wave reflections, arriving at approximately 11 μs following the beginning of the front-surface reflection, are clearly discernible.

Figure 6 shows a B-scan obtained by moving the pulse-echo transducer in the sagittal plane of the plate. We placed a time window over the shear signal in Fig. 5 and swept the beam across the slot in 40 steps of 0.5 mm. This shows the shear-wave reflections from the vertical notch with a depth of 40% of the wall thickness. A B-scan of the plate with the 20% notch indicated that the scan-distance over which the reflection was prominent was shorter. Waveform averaging (8 times) improved the S/N characteristics of the displayed signals. The data in Figs. 5 and 6 demonstrate the feasibility of using our gas-coupled, pulse-echo approach to detect flaws and measure wall thickness in plate geometries.

CONCLUSIONS AND RECOMMENDATIONS

Pressurized gas could be useful as the ultrasonic couplant in a pulse-echo system to detect flaws and measuring thickness in steel plates. It may be possible to exploit this approach for high-speed, in-line, nondestructive inspections of natural-gas pipelines, risers, and similar structures. Further developments in this area will require additional work to improve understanding of the recovery characteristics of the measurement system and the effects of excess absorption due to molecular relaxation and nonlinearities in the gas. The effects of gas motion also need investigation. Because the sound speed in natural gas is greater than in nitrogen, 460 m/s vs. 330 m/s, there should be less sensitivity to alignment and surface roughness.

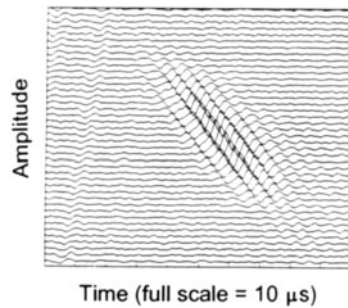


Fig. 6 B-scan of notch reflections made using the shear-wave signal refracted at 45°. The notch (40% of plate thickness) is positioned in the middle of the 20-mm scan. The scan step size was 0.5 mm. The gage pressure of the nitrogen atmosphere was 6.8 MPa (980 psi). The distance between the transducer face and the front specimen surface was 38 mm.

ACKNOWLEDGMENTS

This research was supported by NIST and the Southwest Research Institute Advisory Committee for Internal Research.

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